(54) Title: TORQUE SENSOR

(57) Abstract

T rque in a shaft is measured by a torque sensor comprising at leat one strain gage. The strain gage has a magnetic circuit comprising a magnetostrictive, soft ferromagnetic element (20). A drive mechanism (28) applies a first and a second magnetomotive force to the magnetic circuit. The second magnetomotive force has a sense opposite that of the first magnetomotive force. A sensing mechanism (34) senses the state of magnetization of the ferromagnetic element and a detecting mechanism (45) determines the magnitude of that magnetic field applied to the ferromagnetic element by the second magnetomotive force which reduces the magnetization of the element to zero. Torque is derived from the strain indicated by a change in the coercive of the ferromagnetic element.

DESCRIPTION

TORQUE SENSOR
CROSS REFERENCE TO RELATED APPLICATIONS

5   This patent is a continuation-in-part of Applicant's
Application entitled Magnetic Strain Gage, filed
concurrently herewith which, in turn, is a
continuation-in-part of U.S. Application Serial
Number 136,268, filed December 22, 1987.

10              BACKGROUND OF THE INVENTION

Field of the Invention
    This invention relates to a torque sensor and a
15   method for sensing torque using a measurement of
strain which relies on the increase of coercive
field of certain magnetostrictive, soft
ferromagnetic materials upon application of stress.

20   Description of the Prior Art
    Measurement of torque is frequently required in
the design of industrial machinery.  In order to
determine critical design parameters within various
elements, the designer must be able to measure
25   accurately the mechanical forces, including torque,
to which components may be subjected under operating
conditions.  Measurement of torque is also needed
for the efficient operation of certain machines.
For example, it may be desired for the sake of
30   efficiency to operate an electric motor at a power
level which causes as much torque to be applied to a
load as the shaft connecting the motor to the load
can tolerate without mechanical failure.
    It is known in the art that a cylindrical shaft
35   subjected to a mechanical torque undergoes a
deformation which may be analyzed by the str sses

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therein. More particularly, the stresses in a shaft
subjected only to torque are known to be purely
tensile in the direction of one of the 45° helices
5    of the shaft, while the other 45° helix, which has
opposite chirality or handedness, exhibits purely
compressional stress. A 45° helix is defined
conventionally as a locus of points of constant
radius r from the axis of the cylinder such that
10   points separated by a distance l when measured along
the axis are at polar angles differing by ??
degrees.

Several known sensors for measurement of torque
in a cylindrical shaft rely on use of two strain
15   gages adapted for the measurement of strain at the
surface of the shaft. One of the strain gages is
adapted to measure strain along a first 45° helical
direction. The other strain gage is adapted to
measure strain along a second 45° helical direction
20   of chirality opposite that of the first 45° helical
direction. The torque to which the shaft is
subjected may then be determined from the strains
thus measured by formulae well known in the art.

A typical sensor of the type described above
25   employs resistive strain gages composed of metal or
semiconductor elements. The electrical resistance
of such strain gages changes due to the elongation
or compression of the active element (typically
composed of wire or foil) due to the imparted
30   stress. The resistance is measured using well known
electrical circuitry, frequently a Wheatstone bridge
technique.

A major problem in use of such torque sensors to
measure torque in a rotating shaft is the need to
35   provide electrical connection to th  shaft to supply
energy to drive the strain gages and to transmit
signals indicative of the strain therein. A number
of methods have been employed to overcome this

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difficulty. Slip rings can provide a rotatable
electrical connection between a rotating shaft and
its fixed surroundings. Slip rings however are a
5    source of electrical noise and are not fully
reliable, especially at high rotation rates.
Rotable transformers may be used only if AC
excitation of the strain gages is acceptable.
Generally, resistive strain measurement is less
10   accurate using AC than DC excitation. Another
alternative is use of drive circuitry and a
telemetry transmitter mounted rigidly on the
rotating shaft. Signals indicative of the strain
being sensed by the strain gages are transmitted by
15   radio from the shaft to external receiving means.
Such circuitry is relatively bulky and complex.

     A torque transducer employing stress-sensitive
amorphous ribbon is disclosed by I. Sasada et al.
(IEEE Trans. Magn. MAG-20, 951 (1984)). The
20   transducer relies on a combination of shape
anisotropy and anisotropy resulting from bending an
amorphous ribbon around a shaft. An exciting coil
and two sensing coils are used for the measurement
of magnetic susceptibility (or equivalently of
25   magnetic permebility) of two ribbons applied along
+45° and -45° axes, the angles measured between the
longitudinal direction of each ribbon and the shaft
axis. The dynamic range is disclosed to be longer
than 20 N-m for a 12 mm shaft. However, there is no
30   disclosure in Sasada et al. of a torque transducer
capable of measuring torques in excess of 100 N-m
which are frequently encountered in industrial drive
systems, for example. Furthermore, there is no
disclosure in Sasada et al. of a torque transducer
35   which measures torque by sensing a change in the
magnetic coercivity of a magnetic element.

     There remains a need in the art for torque
sensors which are simple, reliable, and

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operationally independent of electrical connection
to the shaft.

## SUMMARY OF THE INVENTION

The present invention provides a torque sensor
and a method of sensing torque using a measurement
of strain which relies on the increase of the
coercive field of certain magnetostrictive, soft
ferromagnetic materials upon application of stress.
The torque sensor has at least one magnetic strain
gage, comprising a magnetic circuit, a drive means,
a sensing means and a detecting means. The magnetic
circuit comprises a magnetostrictive, soft
ferromagnetic element. The drive means applies a
first and a second magnetomotive force to the
magnetic circuit, the second magnetomotive force
being directed in a direction opposite that of the
first magnetomotive force. The sensing means senses
the state of magnetization of the ferromagnetic
element, and the detecting means determines the
magnitude of magnetic field applied to the
ferromagnetic element by the second magnetomotive
force which reduces magnetization of the
ferromagnetic element to zero.

The torque sensor of the invention is simple to
construct, reliable, and capable of measuring torque
in a shaft over a wide dynamic range. The torque
sensor advantageously requires no electrical
connection to the active sensing element,
facilitating measurement of torque in a rotating
shaft. Output from the sensor indicative of the
torque being measured is readily obtained in digital
form appointed for input directly into various
computer control systems.

## BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood and
further advantages will become apparent when

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reference is made to the following detailed
description and the accompanying drawings, in which;

Figure 1 is a torque sensor of the invention
comprising a single magnetic strain gage;

Figure 2 is a torque sensor of the invention
employing an electromagnetic drive coil excitation;

Figure 3 is a torque sensor of the invention
employing permanent magnet excitation;

Figure 4 is a graph showing input and output
pulses of a magnetic strain gage used in the
invention; and

Figure 5 is a hysteresis curve for a
ferromagnetic material showing the effect of applied
stress.

DETAILED DESCRIPTION OF THE INVENTION

The co-pending applications referenced
hereinabove in the section "CROSS REFERENCE TO
RELATED APPLICATIONS" and incorporated herein by
reference, disclose a magnetic strain gage which
relies on the sensitivity of the magnetic properties
of certain magnetostrictive, soft ferromagnetic
materials to stress. Generally stated, the magnetic
strain gage comprises:

(a) a magnetic circuit comprising a
magnetostrictive, soft ferromagnetric element;

(b) drive means for applying a first and a second
magnetomagnetic force to the magnetic circuit, the
second magnetomotive force having a sense opposite
that of the first magnetomotive force;

(c) sensing means for sensing the state of
magnetization of the magnetostrictive, soft
ferromagnetic element; and

(d) detecting means for det rmining the magnitude of
that magnetic field applied to the magnetostrictive,
soft ferromagnetic element by the second
magnetomotive force which reduces the magnetization

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of the magnetostrictive, soft ferromagnetic element
to zero.  It has been found that the coercive field
of materials adapted to be used as the

5    magnetostrictive, soft ferromagnetic element of the
strain gage has an approximately linear relation to
the stress applied to the material.

A magnetic circuit is a structure comprising at
least one element of ferromagnetic material, the

10   circuit directing and shaping the paths of magnetic
flux.  The simplest such circuit is a single piece
of magnetic material such that the flux lines
emerging from the material either terminate at
external magnetic poles or close through free

15   space.  More complicated magnetic circuits involve a
plurality of pieces of magnetic material, with the
flux lines traversing the air gaps separating the
various pieces.  Magnetomotive forces may be applied
to a magnetic circuit either by incorporating

20   permanent magnets in the circuit or by imposing
magnetic fields produced by the flow of electrical
current through windings.  For the latter, windings
are generally disposed to encircle at least one of
the elements of the magnetic circuit.

25   The magnetic reluctance of a magnetic circuit is
a measure of the difficulty of causing a magnetic
flux to traverse the circuit.  The reluctance of a
circuit is dependent both on the inherent magnetic
properties of the materials used for the elements of

30   the circuit and on the geometrical configuration of
those elements.  Materials for use in the magnetic
circuit of the invention should have high
permeabilities to minimize reluctance.  The
geometrical configuration should be such as to

35   minimize the d magn tizing fields of th  circuit.
If the magnetostrictive, soft ferromagnetic sensing
element of the strain gage is subjected to
demagnetizing fields, its B-H loop will be sh ared

in a manner known in the art. A material having a sheared B-H loop exhibits transitions between the positively and negatively magnetized states which are less abrupt than those characteristic of a material with a non-sheared loop. The resulting voltage pulses induced in secondary coils during operation of the strain gage are broader, making it more difficult to time accurately the peaks of the voltage waveform, thereby reducing the resolution and sensitivity of the strain gage. A magnetic material having a sheared B-H loop also must be driven by a higher magnetic field to insure full alignment of the magnetization within the material, thus necessitating use of more complicated drive means.

The torque sensor and method for measurement of torque of present invention comprise at least one such magnetic strain gage. The magnetostrictive, soft ferromagnetic element of the magnetic strain gage is advantageously affixed to the shaft. Preferably the torque sensor comprises a first magnetic strain gage adapted for measurement of strain along a first helical direction and a second magnetic strain gage adapted for measurement of strain along a second helical direction having a chirality opposite that of the first helical direction. More preferably, the first helical direction is a 45° helix and the second helical direction is a 45° helix of opposite chirality. The torque sensor of the invention may be employed for measuring torque in a shaft which is either stationary or rotating. The apparatus for measuring torque of the invention preferably does not require any electrical connection between the shaft and external apparatus.

A pr ferred class of magnetic circuit for use in the strain gage consists of magnetic circuits with a

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single simply connected, elongated element.  An
elongated body is one having a long dimension much
longer than either of the dimensions in the
directions orthogonal to the long dimension.
Preferably, the longest dimension is at least about
20 times, and more preferably, at least about
100-1000 times the square root of the
cross-sectional area of the body, the cross section
being taken through a plane perpendicular to the
longest dimension.  These requirements on the
geometry of the magnetic element insure that the
element have a small or negligible demagnetizing
factor along the long dimension.  For use in the
strain gage of the invention, the elongated magnetic
element should be mounted with its long dimension
along the axis on which it is desired to measure
strain.

        Referring to the drawing of Figure 1, there is
illustrated one form of a torque sensor 10, which
comprises a single magnetic strain gage 12.  The
embodiment illustrated in Figure 1 is particularly
adapted for the measurement of torque of a single
sense.  Strain gage 12 is adapted to measure stain
along a helical direction 14.  Mangetostrictive,
soft ferromagnetic element 20 of strain gage 12 is
affixed to shaft 24.  Drive means 26 comprises a
drive coil 28 encircling shaft 24.  Drive coil 28 is
connected by electrical leads 13 and 15 to supply
means 30 for causing a cyclical, alternating current
to flow through drive coil 28.  Sensing means 32 of
strain gage 12 comprises a sense coil 34 wound
encircling shaft 24.  Sense coil 34 is electrically
connected by leads 41 and 43 to peak detecting means
45.  Timing means 47 is electrically connected both
to supply means 30 and to peak d tecting means 45.
Timing means 47 senses the differenc  in time
(relative to the waveform of current from supply

means 30) for occurrence of voltage peaks detected
by peak detection means 45 caused by differences in
the strain to which gage 12 is subjected, the
difference in strain being caused, in turn, by the
subjection of shaft 24 to torque.

In the embodiment of Figure 2, peak detecting
means 45 is connected to both of sense coils 34 and
34. The magnentostricture soft ferromagnetic
elements 20 and 22 of strain gages 12 and 16,
respectively, are subjected to magnetic fields which
are substantially equal in magnitude at each instant
in time. Hence, a stress-induced difference between
the coercive fields of elements 20 and 20 will
result in a difference between times at which each
of elements 20 and 20 is subjected to its respective
coercive field and the corresponding times at which
voltage peaks occur in respective sense coils 34 and
34'. Timing means 47 senses the difference in time
between the respective occurrence of peaks in sense
coils 34 and 34' as indicative of the difference in
strain to which gages 12 and 16 are subjected.

In operation, the supply means 30 of Fig. 1
sends an electric current to drive coil 28, thereby
producing a changing magnetic field around drive
coil 28 initiating the reversal of the orientation
of the magnetization within element 20.
Simultaneously with the initiation of the magnetic
pulse, the digital counter within timing means 47 is
turned on. As the magnetic domains within element
20 flip, the changing magnetic flux causes sense
coil 34 to produce an output voltage pulse. This
output voltage pulse is sent to timing means 47
stops the digital counter. The time interval
captured within timing means 47 is retained and
provides the digital output signal. Fig. 4
diagrammatically illustrates this sequence. The top
two lines $X_1$, $X_2$ in Fig. 4 illustrate the electric

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current waveform generated by supply means 30 of
Fig. 1 as shown.  This may be either a sinusoidal
wave $X_1$ or a square wave $X_2$.  The line Y of Fig. 4
5     shows the output voltage pulse wave induced by the
flipping magnetic domains proximate to sense coil 34
when element 20 is not under stress.  There is a
discrete time interval $T_0$ between the time at which
the electric current pulses $X_1$ or $X_2$ of the top
10    lines initiate the magnetization reversal and the
time at which the rate of change of magnetization in
element 20 is maximal, coincident with the voltage
peaks of wave form Y.  The bottom line Z of Fig. 4
shows the effect of strain within the element 20 and
15    illustrates the increase in the discrete time
interval to $T_1$ between when the electric current
pulses in drive coil 28 couple enough magnetic force
to flip the magnetic domains within element 20 and
induce a voltage pulse within sense coil 34.  The
20    time differential $\Delta T$ between $T_0$ and $T_1$, as shown
by the differences between the pulses on the line Y
and the bottom line Z, is used as the measurement of
the strain within the element 20, and hence $\Delta T$ can
be used to determine the strain at the surface of
25    shaft 24 to which the element 20 is attached.
        The change in magnetization force (H) which is
required to initiate the domain reversal in element
29 may best be understood with reference to the
microscopic properties of ferromagnetic materials,
30    and the magnetic hysteresis curves as shown in Fig.
5, wherein the H axis represents the magnetizing
force and the B axis represents the flux density.  B
and H are further related to the internal
magnetization M of the material by the relation $B = H + 4M\pi$.  Within ferromagnetic materials, (also
35    sometimes referred to as simply, magnetic
materials), ther  is a coupling betw en the internal
magnetization of th  material (a vector quantity)

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and the mechanical state of the material, which
reflects, inter alia, any stresses applied to the
material.  A variety of associated phenomena are
known as magnetostriction.  If the magnetization
direction within a magnetic sample is changed then
the sample undergoes changes in its physical
dimensions.  For example, if a magnetic material is
taken from an initial state, in which its
magnetization is randomly distributed, to a final
state, in which its magnetization is entirely
directed along a given direction, then the sample's
length along that direction changes by a fractional
amount known as the saturation magnetostriction
$(\lambda_S)$.  The value of $\lambda_S$ can be either positive or
negative; typical magnitudes of $\lambda_S$ for the
transition metals (Fe, Ni, and Co) are of the order
-10 to 50 parts per million (ppm); for rare earth
transition metal alloys, $\lambda_S$ can be as large as 2000
ppm. $\lambda_S$ provides a measure of the strength of the
magnetoelastic coupling.

For materials having non-zero values of $\lambda_S$, the
application of a uniaxial stress $\sigma$ gives rise to a
magnetoelastic anisotropy energy per unit volume $K_S$
$= \sigma\lambda_S \cos^2 \theta$ where $\theta$ is the angle between the axis
of the stress and the magnetization direction is
determined by an energy balance among the various
sources of magnetic anisotropy and the dipolar
energy $M \cdot H$, where H is the applied field and M is
the magnetization.  In addition to magnetoelastic
anisotropy, there are other sources of anisotropy:
magnetocrystalline anisotropy, shape anisotropy, and
field induced anisotropy.  For materials having $\lambda_S >$
0 which are placed in tension, the magnetoelastic
anisotropy contribution makes it energetically
favorable for the magnetization to align with the
tensile axis.  For application in magnetic strain
gages, the greatest linearity is presum d to be

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achieved by selection of materials in which the
magnetoelastic contributions to the total anisotropy
energy dominates the contributions from the
5      magnetocrystalline and field-induced anisotropy
energies. For sensitivity at low strain levels, it
is preferred that the magnetic material have low
magnetocrystalline and field-induced anisotropy.
This requirement is normally satisfied by so-called
10     soft magnetic materials, i.e. those having low
values of magnetic coercive field $H_c$.

Suitable magnetic materials for the present
invention are soft magnetic materials which are
magnetostrictive, preferably those having $\lambda_s > 10$
15     ppm. A preferred class of magnetic materials to be
employed in the present invention is the class of
magnetic amorphous metals, which are also known as
glassy metals or metallic glasses. Such materials
exhibit metallic electrical and thermal
20     conductivity, and x-ray diffraction patterns like
those of oxide glasses, having broad halos instead
of the sharp peaks seen in crystalline materials.
Among the magnetic amorphous metals are materials
having the general formulas $M_a Y_b Z_c$ and $M_d Y_e$, which
25     are disclosed by U.S. Patent No. 3,856,513 issued to
Chen et al. A variety of techniques are know in the
art for producing these materials in the form of
wires, ribbons, and thin films. In general, the
materials are formed by rapidly quenching the alloy
30     from the melt at rates of at least $10^{4°}$C/s, and more
preferably, of at least $10^{6°}$C/s. Alternatively, the
materials are formed by atomistic deposition
processes such as evaporation and sputtering.

Ferromagnetic amorphous metals exhibit a
35     desirable combination of negligible
magnetocrystalline anisotropy, low magnetic
coercivity, and high hardness and tensile strength.
The high str ngth and hardness are especially

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valuable for the present application. Most conventional crystalline soft magnetic materials which have low anisotropy also have low hardness and tensile strength. They are thus prone to plastic deformation at comparatively low strain levels. In contrast, many amorphous materials show a reversible stress-strain behavior at up to 100 ksi stress. Suitable amorphous materials are thus useful for application in strain gages requiring a stable, reproducible zero strain state and high upper strain limit.

The hysteresis curves of Fig. 5 are shown as representing the magnetic hysteresis loop for ferromagnetic material. In the case of an amorphous iron-based alloy the hysteresis loop is characterized as having a steep slope at its intersection with the H axis. The curve indicated by S1, i.e. bdefghb, is an example of the hysteresis loop for an amorphous metal which is not under any stress or strain, and which for example, would produce the output pulse as illustrated by the center line Y of Fig. 4. Curve S2, i.e. b'd'e'f'h'b', shows a hysteresis loop for the same amorphous iron-based alloy iron when a strain is applied to the alloy, and which would produce the output pulse illustrated by the bottom line Z of Fig. 4. Since the highest slopes on the B-H loop exist at the intersection of the H axis, it is at this point that dB/dt, which is proportional to the induced voltage, is maximum, causing the sharp output pulses of both polarities produced within the sense coil 34.

As discussed above, strain causes a change in the magnetic behavior of magnetostrictive material, which results in the distortion of the hysteresis loop under an applied strain. This distortion generally causes an increase in the width of the

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hysteresis loop with reference to the H axis.
Within the hysteresis loops, for curve S1, $H_C$ and
for curve S2, $H_C'$, represent the magnetizing force
5      at the positive crossing point for curves S1 and S2
on the H axis.  The changes between curve S1 and S2
as a function of applied stress or strain is related
to the change in magnetization force required to
produce a change in the flux density B in element 20
10     when element 20 is under a no-load condition and
when element 20 is subjected to a stress load.  This
generally is the phenomenon upon which the magnetic
strain gage used in the present invention is based.

          It is generally found that the B-H loop of a
15     soft ferromagnetic material is steepest at the
points where the loop crosses the H-axis, i.e., at
the coercive points at which H = $+-H_C$.  If H is
varied periodically in time so as to traverse the
entire B-H loop smoothly, then the waveform of the
20     time rate of change of B (i.e., the wave form of
dB/dt) will exhibit peaks of positive and negative
polarities at those times at which H attains values
of the plus and minus the coercive field $H_C$,
respectively.  The wave form of dB/dt can easily be
25     detected by measuring the voltage induced in a
sensing coil encircling the magnetic material.  By
Faraday's law of induction, the instantaneous
induced voltage is directly proportional to the
instantaneous dB/dt.  It is convenient to choose a
30     cyclic, alternating waveform for the field H(t) in
which  the slope of H(t) changes only twice per
period.  Suitable choices for H(t) include sine,
triangular, and sawtooth waveforms.  H(t) is
conveniently applied by causing an electrical
35     current having the waveform desired to pass through
a winding encircling the magnetic material, since
instantaneous current and field are proportional.
H(t) may be applied continuously or in a burst of a

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finite number of cycles.  The latter is preferred
when it is desired to limit the heat produced by
joule heating of the current-carrying windings.

5          The electric current generated by supply means
30 of Fig. 1 should be of sufficient magnitude to
produce a magnetomotive force which results in a
peak field with strength sufficient to saturate the
magnetization within element 20.  It is presently

10     believed that all of the magnetic domains in the
element 20 tend to orientate or flip simultaneously,
with only small local variations.  Increasing the
stress within element 20 increases the field
strength (H) required to flip or realign the

15     magnetic domains in the directions of H.  This
realignment must follow the hysteresis loop, which,
as has been described, changes with an applied
stress or strain.  The time required for the
magnetic domains to flip is directly linked to the

20     distortion of the hysteresis loop since H is coupled
to element 20 as a function of time.  In effect the
magnetic strain gage measures the increase in time
necessary to supply the additional magnetizing force
to produce a maximum percentage of magnetic domain

25     realignments.
           Referring to the drawing of Figure 1, there is
illustrated one form of a torque sensor 10.  Within
Figures 1-3, common elements will be denoted by the
same numbers.  For simplicity certain elements shown
in Figure 1 will be omitted in Figures 2-3.  In this

30     embodiment the torque sensor 10 comprises two
magnetic strain gages, a first magnetic strain gage
12 adapted for measurement of strain along a first
helical direction 14 and a second magnetic strain
gage 16 adapted for m asurement of strain along a

35     second helical direction 18 having chirality
opposite to that of the first helical dir ction 14.
The magnetostrictive, soft ferromagnetic elements 20

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and 22, respectively, of each of the first and the
second magnetic strain gages 12 and 16 are affixed
to shaft 24.  The first and second magnetic strain

5    gages share a common drive means 26 comprising a
drive coil 28 wound encircling shaft 24 and means 30
for causing a cyclic, alternating electrical current
to flow through drive coil 28.  The sensing means,
32 and 32', respectively, for each strain gage

10   comprises a sense coil 34 and 34' wound encircling
shaft 24.  For measurement of torque in a
non-rotating shaft, drive coil 28 and sense coils 34
and 34' may be wound directly on the shaft.  For
applications which require the measurement of torque

15   in a rotating shaft, drive coil 28 and sense coils
34 should be mounted rotatably independent of the
shaft to eliminate the need for electrical
connection to the shaft.

Another embodiment of the apparatus for

20   measuring torque adapted for use with a rotating
shaft 24 is illustrated in Fig. 3.  This embodiment
again comprises two magnetic strain gages, a first
magnetic strain gage 12 adapted for measurement of
strain along a first helical direction 14 and a

25   second magnetic strain gage 16 adapted for
measurement of strain along a second helical
direction 18 having chirality opposite to that of
the first helical direction 14.  The
magnetostrictive, soft ferromagnetic elements 20 and

30   22, respectively, of each of the first and the
second magnetic strain gages 12 and 16 are affixed
to shaft 24.  The first and second magnetic strain
gages 12 and 16 share a common drive means 26
comprising a first permanent magnet 50 and a second

35   permanent magnet 52.  The first and the second
permanent magn ts 50 and 52 are dispos d
diametrically opposite each other across shaft 24.
First permanent magnet 50 has its north magnetic

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pole located proximate to shaft 24 and second
permanent magnet 52 has its south magnetic pole
proximate to shaft 24.  As shaft 24 rotates relative

5    to permanent magnets 50 and 52, an end of each of
the magnetostrictive, soft ferromagnetic elements 20
and 22 passes proximate to first permanent magnet 50
and second permanent magnet 52 sequentially.  When
each magnetic element passes proximate to first

10   permanent magnet 50 a magnetomotive force is
progressively applied, bringing the element first to
magnetic saturation, then to remanence.  As each
magnetic element then approaches proximate to second
permanent magnet 52, an oppositely directed

15   magnetomotive force of increasing strength is then
applied.  At the point at which the magnetomotive
force imposes on each magnetic element a magnetic
field having a strength equal to the coercive field
of each respective magnetic element, the net

20   magnetization of the magnetic element is reduced to
zero.  Each of the first and second magnetic strain
gages 12 and 16 comprises a sense coil 34 proximate
to, and preferably surrounding, shaft 24.  A voltage
is induced in each of sense coils 34 and 34'

25   corresponding to a change in the magnetization of
the associated magnetic element, the voltage
reaching a peak at the time at which the
magnetization reverses and the imposed magnetic
field is equal to the element's coercive field.  By

30   sensing changes in the relative phase of the induced
voltage peaks detected in the respective sense coils
34 and 34', changes in the coercive fields of the
magnetic elements 20 and 22 can be sensed.  In this
embodiment the phase of the induced voltage peaks
should be measured r lative to the rotational

35   position of the shaft which can be s ns d by means
known in the art, such as optical encoders and
magnetic position encoders.

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The embodiment depicted in Fig. 3 can also be
practiced using any even number of permanent magnets
symmetrically disposed about shaft 24, the permanent
magnets having alternating north and south magnetic
poles proximate to shaft 24.  In a most preferred
embodiment, the torque sensor comprises two magnetic
strain gages.  The magnetostricture, soft
ferromagnetic elements of the two gages are
substantially identical amorphous metal ribbons or
wires which are affixed synmetrically to the shaft
along helices of +45° and -45°.  The starting ends
of the elements are located substantially at the
same polar angle.  A single drive coil, encircling
the shaft, is located midway between the starting
ends of the elements.  Two substantially identical
sense coils encircling the shaft are disposed near
the ends of the elements and are located equidistant
from the drive coil.  A cyclic, alternating current
passed through the drive coil produces substantially
identical magnetic fields in the two elements.  A
difference in the phase of the voltage pulses
induced in the sense coils is thereby indicative of
a difference in strain along the helices, and thus
of the torque imparted to the shaft.

While not being bound by any theory, it is
believed at this time by the inventor that the
coercivity of magnetostrictive materials having
positive saturation magnetostriction is affected
principally by tensile stresses and only to a lesser
extent by compressive stresses.  It is likewise
believed that the coercivity of materials having a
negative saturation magnetostriction is affected
principally by compressive stresses.  Hence, a
greater shift in phase is to be expected for the
strain gag  undergoing tensile stress than for the
strain gage in compressive stress, both gages
employing positive magnetostriction material.

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Likewise, a lesser shift in phase is to be expected
for the strain gage undergoing tensile stress than
for the strain gage in compressive stress, both
5    gages employing negative magnetostriction material.

      Having thus described the invention in rather
full detail, it will be understood that this detail
need not be strictly adhered to but that various
changes and modifications may suggest themselves to
10   one skilled in the art, all falling within the scope
of the present invention as defined by the subjoined
claims.

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WHAT IS CLAIMED IS:

5    1.    A torque sensor for measurement of torque in a shaft
comprising at least one magnetic strain gage, said strain
gage comprising:
         (a) a magnetic circuit comprising a magnetostrictive, soft
10   ferromagnetic element;
         (b) drive means for applying a first and a second
magnetomagnetic force to said magnetic circuit, said
second magnetomotive force having a sense opposite that of
said first magnetomotive force;
15       (c) sensing means for sensing the state of magnetization
of said ferromagnetic element; and
         (d) detecting means for determining the magnitude of that
magnetic field applied to said ferromagnetic element by
said second magnetomotive force which reduces the
20   magnetization of said ferromagnetic element to zero.


     2.    The torque sensor recited in claim 1, wherein said
ferromagnetic element is affixed to said shaft.


25   3.    The torque sensor recited in claim 1, comprising a
first magnetic strain gage adapted for measurement of
strain along a first helical direction of said shaft and a
second magnetic strain gage adapted for measurement of
strain along a second helical direction of said shaft
30   having chirality opposite to that of said first helical
direction, the ferromagnetic element of each of said first
and said second magnetic strain gages being affixed to
said shaft.


35   4.    The torque sensor recited in claim 3, wh r in said
first helical dir ction is a 45° helix and said second
helical direction is a 45° helix of chirality opposite
that of said first helical direction.

5.    The torque sensor recited in claim 3, wherein said
drive means of said first and said second magnetic strain
5    gages comprise at least one drive coil encircling said
shaft and supply means for causing an electrical current
to flow in said at least one drive coil.

6.    The torque sensor recited in claim 3, wherein said
10    drive means of said first and said second magnetic strain
gages comprises an even number of permanent magnets,
proximately disposed about said shaft, alternate magnets
having north and south magnetic poles nearest said shaft.

15    7.    The torque sensor recited in claim 3, comprising two
permanent magnets.

8.    The torque sensor recited in claim 3, wherein said
sensing means for said first magnetic strain gage and said
20    sensing means for said second magnetic strain gage each
comprises a sense coil encircling said shaft.

9.    A method for measurement of torque in a shaft,
comprising:
25    (a) attaching at least one magnetic circuit to said shaft,
said magnetic circuit comprising a magnetostrictive, soft
ferromagnetic element; and
(b) sensing a change in the coercive field of said
ferromagnetic element caused by torque in said shaft.

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10.    A method for measurement of torque in a shaft
comprising:
(a) attaching a first magnetic strain gage and a second
magnetic strain gage to said shaft, each of said first and
second magnetic strain gages comprising magnetostrictive,
35    soft ferromagnetic element and being adapted to sense a
change in the coerciv  field of said f rromagnetic
element, said first magnetic strain gage being adapted to

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measure strain along a first helical direction of said
shaft.and said second magnetic strain gage being adapted
to measure strain along a second helical direction of said
shaft having chirality opposite to that of said first
helical direction; and
(b) measuring the strains indicated by said first and said
second magnetic strain gages.


11.   The torque sensor recited in claim 3, wherein said
drive means of said first and said second magnetic strain
gages comprise at least one drive coil encirling said
shaft and means for causing a cyclic, alternating current
to flow in said at least one drive coil, said sensing
means of said first magnetic strain gage comprises a first
sense coil, said sensing means of said second magnetic
strain gage comprises a second sense coil, each of said
sense coils encircling said shart, and said torque sensor
further comprises:
(e)   peak-detecting means electrically conneted to said
sense coils for detecting peaks in the voltages appearing
across each of said sense coils; and
(f)   timing means electrically connected to said
peak-detecting means, said timing means being adapted to
sense the difference in phase between said peaks in said
sense coils.


12.   A method as recited in claim 10, wherein said first
magnetic strain gage further comprises a first sense coil
and said second magnetic strain gage further comprises a
second sense coil and said method further comprises:
subjecting each of said ferromagnetic elements to cyclic
alternating magnetic fields having substantially, equal
magnitudes at each of said ferromagnetic elements and
sensing the difference in phase of the voltage peaks
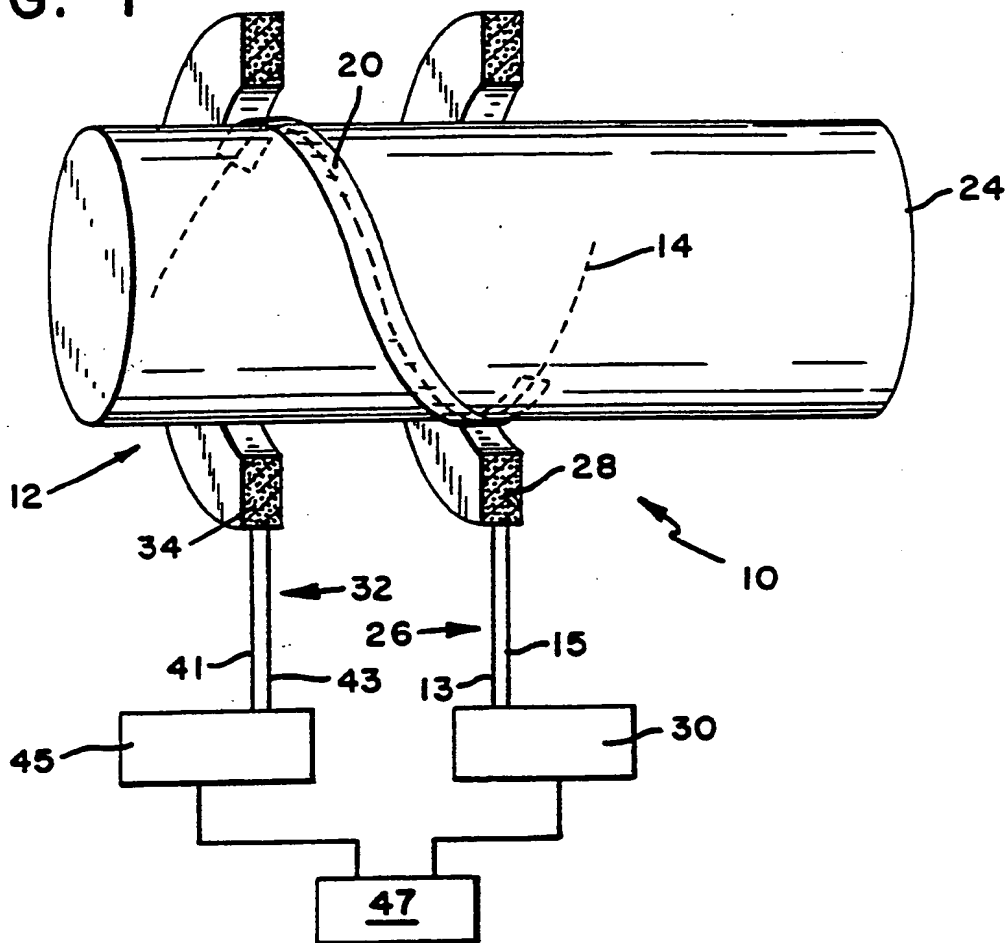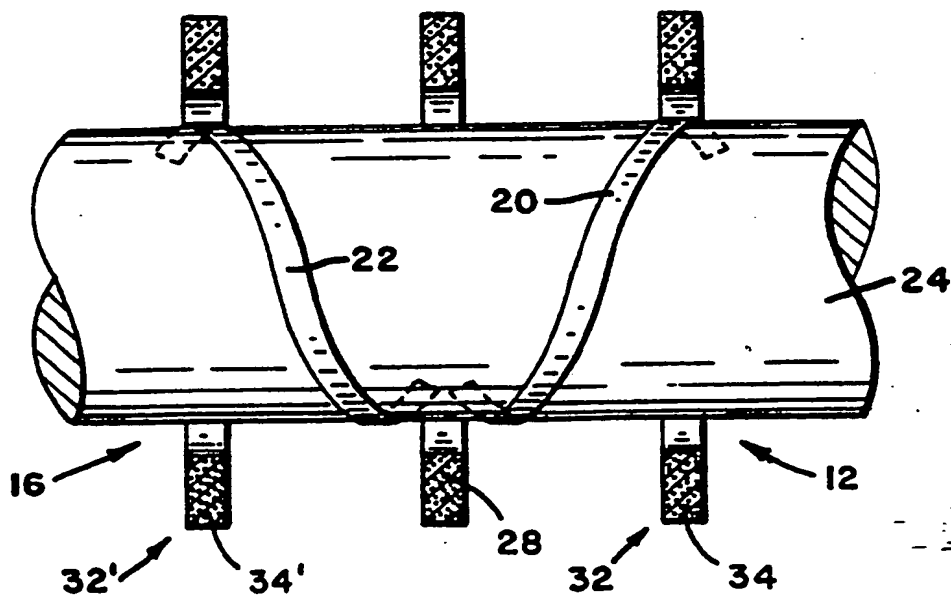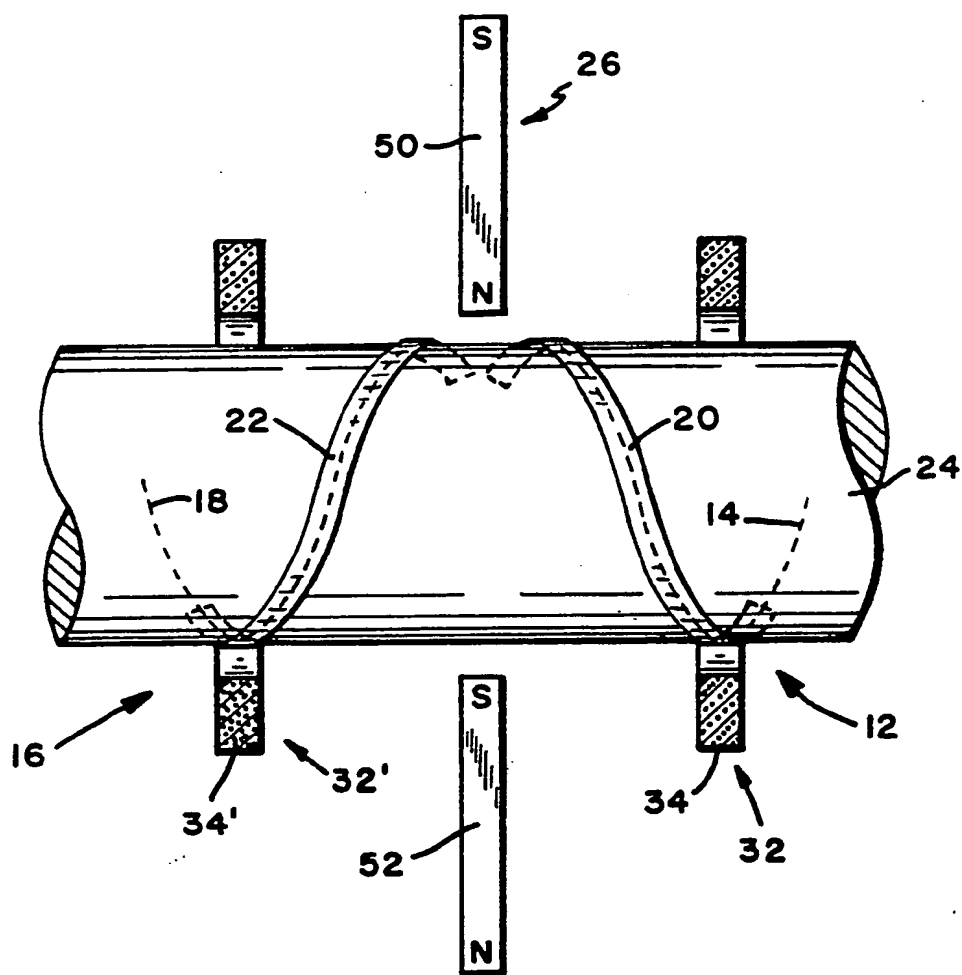induced in said first and said second sens  coils.

# FIG. 1

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41    43    13    15

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# FIG. 2

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32'    34'    28    32    34

# F I G. 3

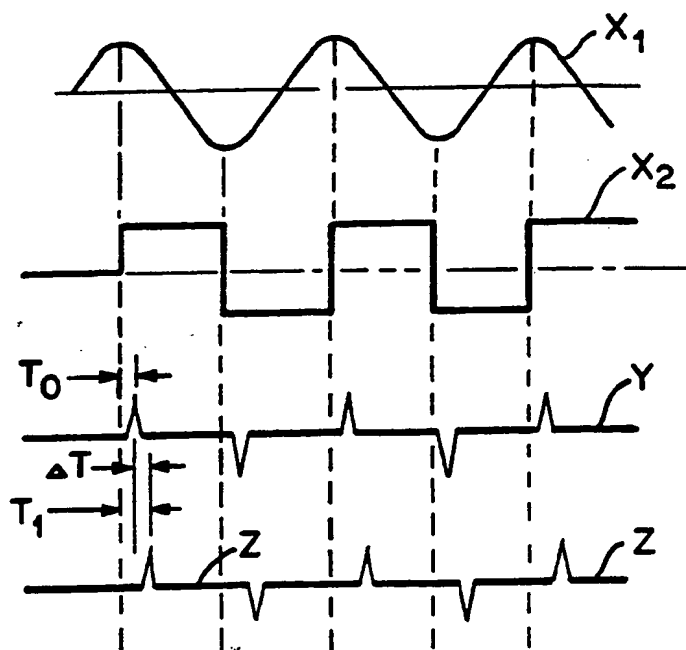**F I G. 4**



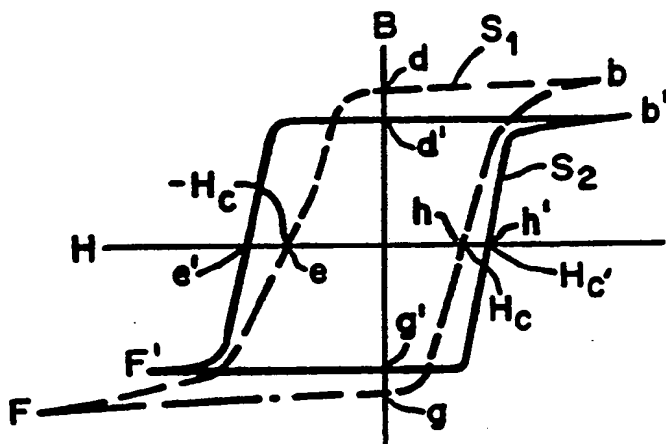**F I G. 5**

# INTERNATIONAL SEARCH REPORT

International Application No

## I. CLASSIFICATION OF SUBJECT MATTER    (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5      G01L3/10

## II. FIELDS SEARCHED

### Minimum Documentation Searched[7]

| Classification System | Classification Symbols |
|---|---|
| Int.Cl. 5 | G01L |

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

## III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

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° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

## IV. CERTIFICATION

| Date of the Actual Completion of the International Search | Date of Mailing of this International Search Report |
|---|---|
| 05 SEPTEMBER 1991 | 2 2 10. 91 |

| International Searching Authority | Signature of Authorized Officer |
|---|---|
| EUROPEAN PATENT OFFICE | VAN ASSCHE P.O. |

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The members are as contained in the European Patent Office EDP file on
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